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Development of a novel biofedelic skull-neck-thorax model capable of quantifying motions of the aged cervical spine

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ABSTRACT

Study Design. An *in vitro* biomechanical study.

Objectives. The objectives were to: develop a new biofidelic skull-neck-thorax model capable of quantifying motion patterns of the cervical spine in the presence of a halo-vest, investigate the effects of vest loosening, superstructure loosening, and removal of the posterior uprights, and evaluate the ability of the halo-vest to stabilize the neck within physiological motion limits.

Summary of Background Data. Previous clinical and biomechanical studies have investigated neck motion with the halo-vest only in the sagittal plane or only at the injured spinal level. No previous studies have quantified three-dimensional intervertebral motion patterns throughout the injured cervical spine stabilized with the halo-vest or studied the effect of halo-vest components on these motions.

Methods. The halo-vest was applied to the skull-neck-thorax model. Six osteoligamentous whole cervical spine specimens (occiput through T1 vertebra) were used that had sustained multiplanar ligamentous injuries at C3/4 through C7/T1 during a previous protocol. Flexibility tests were performed with normal halo-vest application, loose vest, loose superstructure, and following removal of the posterior uprights. Average total range of motion (RoM) for each experimental condition was statistically compared ($P<0.05$) to the physiological rotation limit for each spinal level.

Results. Cervical spine snaking was observed in both the sagittal and frontal planes. The halo-vest, applied normally, generally limited average spinal motions to within average physiological limits. No significant increases in average spinal motions above physiological were observed due to loose vest, loose superstructure, or removal of the posterior uprights. However, a trend towards increased motion at C6/7 in lateral bending was observed due to loose superstructure.

Conclusions. The halo-vest, applied normally, effectively immobilized the cervical spine. Sagittal and frontal plane snaking of the cervical spine due to the halo-vest may reduce its immobilization capability at the upper cervical spine and cervicothoracic junction.

Keywords. Halo-vest; Orthosis; Cervical Spine; Motion; Snaking

KEY POINTS

- A skull-neck-thorax model was used to investigate neck motion patterns due to the halo-vest and to determine the effects of vest loosening, superstructure loosening, and removal of the posterior uprights on these motions. The neck specimens had ligament injuries at the middle and lower cervical spine regions.
- The halo-vest, applied normally, effectively immobilized the cervical spine. No significant motions beyond average physiological limits were observed due to improper halo-vest application, however a trend towards increased motion at C6/7 in lateral bending was observed due to loose superstructure.
- Cervical spine snaking occurred in the sagittal and frontal planes, with rotation opposite to the direction of loading observed at either the upper or lower cervical spine. These motions may reduce the immobilization capability of the halo-vest at the upper cervical spine and cervicothoracic junction.

MINI ABSTRACT

The effects of halo-vest components on neck stability were determined, including loose vest, loose superstructure, and removal of the posterior uprights. When applied normally, the halo-vest effectively stabilized the cervical spine. Sagittal and frontal plane snaking of the cervical spine was observed due to the halo-vest, which may reduce its immobilization capability at the upper cervical spine and cervicothoracic junction.

INTRODUCTION

Nearly five decades ago, Perry and Nickel[1] developed the halo-vest orthosis to provide rigid cervical spine stabilization for treatment of patients with severe scoliosis or neck muscle paralysis due to poliomyelitis. They subsequently reported a successful 11-year clinical follow-up.[2] Since then, the halo-vest has been widely used to immobilize the neck in pre- or post-operative settings or as definitive treatment for those with cervical spine injury or deformity. The halo-vest provides the greatest neck immobilization as compared with other orthoses.[3,4] While specific indications for use remain debated, the halo-vest has been used either exclusively or together with surgical fusion to successfully treat neck deformity, fractures, and dislocations.[5-11] Controversy regarding indications for use may be due to conflicting results of clinical studies[12-14] and a lack of previous biomechanical research investigating neck motion with the halo-vest and the role of halo-vest components on stabilization of the injured cervical spine.

Previous clinical and biomechanical studies have quantified cervical spine motion restriction due to the halo-vest. The clinical studies used radiographic or fluoroscopic techniques to evaluate sagittal neck motion in symptomatic patients treated with a halo-vest[3,4,15-18] or asymptomatic volunteers fitted with a modified, non-invasive halo-vest.[19,20] Neck motion was measured due to voluntary active neck flexion/extension or activities of daily living including transitioning between supine, seated, and upright postures. These data indicated that the halo-vest provided the greatest motion restriction at spinal levels inferior to the C2 vertebra and the least above C2.[3,16,17] These studies also demonstrated sagittal plane snaking of the cervical spine due to the halo-vest, defined as flexion rotation at a spinal level with simultaneous extension at adjacent levels.[3,17,18] However, these *in vivo* studies have limitations. Non-sagittal rotations of individual spinal levels due to axial torque or lateral bending were not evaluated. The applied neck loads are unknown and most likely varied among patient/volunteer due to varying pain thresholds and neck muscle strength. The studies of asymptomatic volunteers did not provide insight into the effectiveness of the halo-vest for stabilizing the injured cervical spine. The previous *in vitro* biomechanical studies have measured motion only at one or two spinal levels to evaluate the effectiveness of the halo-vest in stabilizing cadaveric neck specimens following simulated injuries.[21-24]

No previous biomechanical studies have determined the three-dimensional intervertebral motion patterns throughout the injured cervical spine in the presence of a halo-vest or studied the effect of halo-vest components on these motions. These data may provide information to the clinician when prescribing the halo-vest based upon specific pathological conditions and may be used towards improving halo-vest design. The purpose of the present study was to develop a new biofidelic skull-neck-thorax model capable of quantifying motions of cervical spine specimens in the presence of a halo-vest and to use this model to investigate the effects of vest loosening, superstructure loosening, and removal of the posterior uprights. The specimens had ligament injuries at the middle and lower cervical spine regions. The ability of the halo-vest to stabilize the cervical spine was evaluated by comparing motion at each spinal level with physiological motion limits.

MATERIALS AND METHODS

Overview

The skull-neck-thorax model was prepared using six osteoligamentous whole cervical spine specimens that were mounted in resin at the occiput and T1 vertebra. The specimens underwent a previous protocol of incremental left-side impacts and pre- and post-impact flexibility tests.[25,26] To document physiological motion limits, the intact specimens underwent flexibility tests up to peak pure moments of 1.5, 3, and 1.5 Nm in flexion-extension, axial torque, and lateral bending, respectively.[25] These moments produced physiological spinal rotations, without causing injury. Left-side impacts were applied at 3.5, 5, 6.5, and 8 g horizontal accelerations of the T1 vertebra.[26] Multiplanar ligamentous injuries, in the form of biomechanical instability, were documented at the middle and lower cervical spine, C3/4 through C7/T1. Macroscopically identifiable injuries observed following the 8 g impact included right capsular ligament tears at C3/4 through C7/T1, excluding C5/6. Following the 8 g impact, the specimens were frozen at -20°C prior to preparation for flexibility testing with the halo-vest.[27]

Skull-Neck-Thorax Model with the Halo-Vest

The skull-neck-thorax model consisted of the whole cervical spine specimen, plastic skull, and mannequin thorax with the halo-vest (**Figure 1**).[21] The whole cervical spine was anatomically positioned between the plastic skull and the mannequin thorax. The plastic skull was rigidly fixed to the occipital mount while the T1 mount was rigidly fixed to the mannequin thorax. The skull circumference was 52 cm, while the circumference of the mannequin chest was 88 cm at the xiphoid process. The average age of the specimens was 82.5 years (range: 74 to 98 years) with four male and two female donors. Apart from typical age-related degenerative changes, the donors did not suffer from any disease that could have affected the osteoligamentous structures. To attach motion measuring flags, a custom plastic support was fitted rigidly onto the anterior aspect of each vertebra (C1 through C7). The flags, each with three non-collinear markers, were rigidly fixed onto the plastic supports. Additional flags were rigidly mounted to the skull and thorax. A lateral radiograph of the specimen in the neutral posture, with motion tracking flags, was taken to establish anatomic coordinate systems fixed to each vertebra. A ReSolve Halo System (Ossur Americas, Aliso Viejo, CA, USA) was applied to the model according to the manufacturer's instructions, as it would be applied in a clinical setting. An open back, glass composite halo ring (standard size) was fixed to the skull using four ceramic-tipped skull pins. The pins were tightened to 0.68 Nm (6 inch-lbs) in opposing pairs. The superstructure components, including two anterior and two posterior uprights, connected the halo ring to the vest (medium size). The thorax was fitted with a shirt. The vest was secured to the thorax with two shoulder straps and two waist straps. This allowed for motion of the vest relative to the thorax. To prepare the model for flexibility testing, a loading jig was applied to the occipital mount, while the thorax was fixed to the test table. The combined weight of the loading jig, occipital mount, skull, and halo ring was counterbalanced throughout the flexibility tests.

Three-Plane Flexibility Testing

Three-plane flexibility testing was initially performed with the halo-vest applied normally and was repeated to evaluate the effects of vest loosening, superstructure loosening, and removal of the posterior uprights. Vest loosening was achieved by loosening the two shoulder and the two waist straps each by one inch relative to normal vest application. Superstructure loosening was achieved by loosening all bolts of the superstructure, with the exception of the two bolts connecting the superstructure to the halo ring, which were tightened rigidly.

Flexibility tests were performed by applying pure moments to the occipital mount in four equal steps up to 10 Nm in flexion-extension, axial torque, and lateral bending (**Figure 2**).[28] At each moment step, the loading was held constant for 30 seconds to allow for viscoelastic creep, after which time kinematic data were recorded. Two preconditioning cycles were performed and data were recorded on the third loading cycle. A custom-built loading apparatus was used for automated flexibility testing. The kinematic data were measured using the Optotrak three-dimensional motion measuring system (Optotrak

3020, Northern Digital, Waterloo, Ontario, Canada). Using the specimen radiograph, anatomic coordinate systems were established to determine the motion of each vertebra relative to the adjacent inferior vertebra **(Figure 3)**. The Euler angles were calculated at each load increment for each spinal level, C0/1 through C7/T1, and head/T1 in the sequence Rx, followed by Ry and Rz.[29,30]

Error Analyses

A custom jig was designed to determine the overall error in the calculation of intervertebral rotations, which included errors associated with the measurement and computational systems. The jig consisted of two motion measuring flags, each with three non-collinear markers. The upper flag was rotated around each of the three axes of the ground coordinate system, XYZ (**Figure 1**), using a precision rotator (resolution 0.001°, Oriel Corporation, Stamford, CT) in 10 increments of 1° each while the lower flag remained fixed. The kinematic data were recorded at each motion step. The error was defined as the difference between the computed and exact rotation. The average (SD) error in the 10° range was -0.05° (0.05°), -0.03° (0.04°), and -0.01° (0.02°) for rotations around the X, Y, and Z axes, respectively.

Data Analyses

Average rotation-moment curves were plotted for each spinal level and head/T1 in each motion plane and for each experimental condition: normal halo-vest application, loose vest, loose superstructure, and removal of the posterior uprights. Total range of motion (RoM) (**Figure 2**) was computed for each spinal level and in each motion plane. The physiological motion limit was defined at each spinal level as the total RoM obtained from the intact flexibility tests.[25] Single factor, repeated measures analysis of variance and Bonferroni post-hoc tests were performed to determine significant increases in the average total RoM at each spinal level for each experimental condition relative to the physiological motion limit. Significance was set at $P<0.05$ with a trend towards significance at $P<0.1$. Adjusted P-values were computed based upon the 96 post-hoc tests performed.

RESULTS

The average rotation-moment curves with standard deviations are presented in graphical form for flexion/extension (**Figure 4A**), axial torque/rotation (**Figure 4B**), and lateral bending (**Figure 4C**). These data are provided for each spinal level, C0/1 through C7/T1, and head/T1 for normal halo-vest application, loose vest, loose superstructure, and removal of the posterior uprights. In each motion plane, head/T1 consistently rotated in the direction of the applied moment. However, rotation directions for individual spinal levels varied with the direction of applied load in each motion plane, as described below.

General motion patterns in flexion/extension were dependent upon halo-vest application (**Figure 4A**). With normal halo-vest application and loose vest, rotation opposite to the direction of the applied moment was observed at C0/1 and C1/2, while inferior spinal levels rotated in the direction of the applied moment. Similar motion patterns were observed due to removal of posterior uprights, with the exception that C1/2 consistently rotated in flexion. These motion patterns are in contrast to those observed with loose superstructure, which caused rotation in the direction of the applied moment at C0/1 through C3/4 and opposite to the direction of the applied moment at C5/6 through C7/T1. The highest average total RoM among all experimental conditions studied was 29.7° at C0/1 followed by 20.9° at C1/2, both due to loose superstructure.

The highest average total RoM was observed at C1/2 due to axial torque, as compared to other spinal levels, for each experimental condition studied (**Figure 4B**). At C1/2, rotation in the direction of the applied moment was consistently observed, with the average total RoM increasing from 4.2° with normal halo-vest application to 22.3° with loose superstructure.

Consistent rotation-moment patterns were observed in lateral bending (**Figure 4C**). For all conditions studied, rotation opposite to the direction of the applied moment was observed at C0/1 through C2/3, while inferior spinal levels, C3/4 through C7/T1, rotated in the direction of the applied moment. The highest average total RoM of 11.5° was observed at C0/1 followed by 10.7° at C6/7, both due to loose superstructure.

No significant increases in average total RoM above physiological limits were observed at any spinal level or in any motion plane in the presence of the halo-vest (**Table 1**). The average total RoMs at each spinal level with the halo-vest were generally less than the physiological rotation limits in all motion planes, with the exception of C0/1 and C1/2 in flexion/extension and C0/1 and C4/5 through C7/T1 in lateral bending. At the upper cervical spine, these increases were marginal, reaching 2.4° at C0/1 in lateral bending due to loose superstructure. At the lower cervical spine in lateral bending, a trend towards increased average total RoM of 6.6° was observed at C6/7 due to loose superstructure.

DISCUSSION

The halo-vest orthosis, introduced in 1959 by Perry and Nickel[1] to treat those with severe scoliosis or neck muscle paralysis, has been used since then for pre- or post-operative stabilization or definitive treatment of cervical spine injuries.[5-11] The present study, using a skull-neck-thorax model, determined the spinal motion patterns in the presence of the halo-vest (**Figure 1**) and evaluated the effect of halo-vest components on these motions, including loose vest, loose superstructure, and removal of the posterior uprights. The present specimens had been previously left-side impacted causing predominately lateral ligamentous injuries at the middle and lower cervical spine, C3/4 through C7/T1, with the most severe instability documented at C6/7.[25,26] Associated or multiple ligamentous injuries may exist at the injured or adjacent spinal levels in patients with cervical spine fracture who are treated with the halo-vest.[31-33] These present specimens were used to investigate the effectiveness of the halo-vest for limiting motions in the presence of multiple neck ligament injuries. The present kinematic results demonstrated snaking of the cervical spine due to the halo-vest in both the sagittal (**Figure 4A**) and frontal (**Figure 4C**) planes, evidenced by rotation in the direction opposite to that of the applied moment at either the upper or lower cervical spine with simultaneous rotation of adjacent spinal levels in the direction of the applied moment. Cervical spine snaking in the transverse plane was not observed (**Figure 4B**).

The halo-vest, applied normally, generally limited average intervertebral motions throughout the cervical spine to within physiological limits (**Table 1**) thereby protecting the unstable spine from further potentially injurious motions. No significant increases in average spinal rotations above physiological limits were observed due to loose vest, loose superstructure, or removal of the posterior uprights. However, motions in excess of physiological were generally observed at both the upper and lower cervical spine in flexion/extension and lateral bending. These results are supported by clinical studies which have demonstrated that the halo-vest provided the least motion restriction at spinal levels above C2.[3,16,17] We observed a trend towards increased motion above physiological at C6/7 in lateral bending due to loose superstructure. The present results indicate that improper halo-vest application or patient non-compliance, particularly causing loose superstructure, may diminish neck immobilization, leading to potentially injurious motion in those with associated neck ligament injuries.

The present study has limitations that should be considered before interpreting the results. The average age of the present specimens was 82.5 years. The present specimens had ligament injuries at the middle and lower cervical spine regions, with no injuries at the upper cervical spine. We did not study the neck stabilizing properties of the halo-vest in the presence of Jefferson, odontoid, facet, or compression fractures, though these may be studied in future work using the present skull-neck-thorax model. Neck muscle forces were not simulated, nor was follower load applied, thus we evaluated the stabilization capabilities of the halo-vest using a passive cervical spine model. A plastic skull was used in place of the human osseous skull, thus the bone/halo-pin interface was not simulated. The halo pins were initially tightened to 6 inch-lbs which provided strong fixation of the halo ring to the plastic skull. No pin loosening was observed throughout the flexibility tests. Pure moments up to 10 Nm were applied to the cervical spine in the presence of the halo-vest. Although the *in vivo* neck loads of symptomatic patients wearing the halo-vest are unknown, Fukui et al[28] documented static superstructure loads up to 10 Nm in patients wearing the halo-vest while performing activities of daily living. A single orthosis was utilized with one skull-thorax model, thus the effects of different halo-vest designs or changes in body habitus were not studied. Thoracic spine motions were not considered. We did not determine neck motion patterns due to transitioning between supine, seated, and upright postures. Previous clinical studies have documented excessive spinal motions during these maneuvers, particularly from supine to upright postures, if thorax motion is allowed within a loose fitting vest while the skull remains immobilized.[17,18]

The present average total RoM in flexion/extension with normal halo application may be compared with previously reported average *in vivo* data (**Figure 5**).[3,4,16-18] The *in vivo* data were obtained from radiographic studies of symptomatic patients wearing a halo-vest while performing voluntary active neck flexion/extension or activities of daily living, including transitioning between supine, seated, and upright postures. Our data are in good agreement with the *in vivo* data, within 2°, at C0/1 and at the lower cervical spine, C5/6 through C7/T1. The present motions at C1/2 through C4/5 are less than the *in vivo* data with the greatest difference of 4° observed at C2/3. These differences may be attributed to several factors. The present study utilized a newer halo-vest design, which may provide greater neck immobilization as compared with those used in the previous studies. The present mannequin thorax was rigid and did not simulate soft tissue deformation. In the clinical studies, vest loosening may have occurred in volunteers with pendulous breasts or an obese abdomen, thus reducing the immobilization capability of the halo-vest. Greater computations errors may have existed in the clinical studies due to difficulties identifying radiographic bony landmarks and intra-observer errors. Lastly, the neck injuries in the clinical studies may have be more severe than those of the present specimens, causing greater cervical spine instability.

There are few previous biomechanical studies with which our results may be compared.[21-24] Mirza et al[21] used the skull-neck-thorax model to study the neck stabilizing properties of a halo-vest using C2 through T2 specimens. Ligaments were transected at C5/6 creating severe instability at this spinal level. Anterior, posterior, and lateral horizontal shear forces of 158 N were applied to the skull causing large bending moments in the neck. The effects of loose vest, loose superstructure, vest-thorax friction, and vest deformation on C5/6 motions were investigated. Although direct comparisons to our data are difficult due to the differing load conditions and ligament injury severity, the previous study also observed increased neck motion due to loose vest and loose superstructure.

The present study documented cervical spine snaking in both the sagittal and frontal planes. The former results are consistent with clinical studies[3,17,18] which have documented snaking in symptomatic patients wearing a halo-vest while performing voluntary active neck flexion/extension or activities of daily living including transitioning between supine, seated, and upright postures.[3,17,18] Frontal plane snaking was observed in the present study, as lateral bending moments caused rotation in the direction opposite to that of the load direction at the upper cervical spine, C0/1 through C2/3, while inferior spinal levels, C3/4 through C7/T1, rotated in the direction of the applied load. A similar frontal plane S-shaped neck curvature was documented, *in vivo*, without the halo-vest due to physiologic lateral head translation.[34] These cumulative results have clinical implications. Although the head/T1 motions of symptomatic patients wearing a halo-vest may be small, large intervertebral motions may be present, particularly at the upper cervical spine or cervicothoracic junction. These motions, if above physiological limits, may cause further ligamentous injury, re-dislocation, or delays in healing or arthrodesis.

Neck motion patterns due to the halo-vest were documented in the present study using a new biofidelic skull-neck-thorax model. The halo-vest, when applied normally, effectively immobilized the cervical spine within the average physiological motion limits. Cervical spine snaking due to the halo-vest may potentially lead to motions beyond physiological limits at the upper cervical spine or cervicothoracic junction. The present data provide insight into the neck motion patterns due to the halo-vest and may assist clinicians when prescribing the halo-vest based upon the underlying pathology.

REFERENCES

Table 1. Average (SD) total ranges of motion in degrees in A) flexion/extension, B) axial rotation, and C) lateral bending. Statistically significant increases ($P<0.05$) with respect to the physiological limits are indicated by *, while trends ($P<0.1$) are indicated by $^{\#}$.

	C0/1	C1/2	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1
A) Flexion/Extension								
Physiological	28.4 (6.0)	19.8 (7.6)	9.2 (2.3)	10.8 (5.2)	10.6 (5.3)	14.9 (4.8)	12.1 (5.1)	5.9 (1.1)
Normal Halo-Vest Application	5.8 (4.3)	2.1 (2.2)	0.4 (0.3)	1.6 (2.4)	2.0 (3.1)	4.8 (2.0)	5.7 (3.4)	3.8 (2.0)
Vest Loose	8.3 (5.4)	6.9 (5.1)	1.4 (1.0)	3.1 (3.5)	3.5 (3.9)	8.6 (2.4)	8.4 (4.5)	5.4 (3.2)
Removal of Posterior Uprights	17.1 (6.8)	2.8 (1.9)	4.6 (3.0)	4.9 (3.0)	8.3 (3.8)	9.5 (4.4)	6.0 (1.8)	3.4 (2.5)
Superstructure Loose	29.7 (7.6)	20.9 (6.4)	6.6 (3.9)	5.4 (2.7)	4.7 (4.4)	7.4 (4.5)	6.7 (5.0)	5.0 (2.2)
B) Axial Rotation								
Physiological	13.9 (2.2)	58.2 (16.8)	7.9 (2.4)	9.2 (2.3)	10.9 (5.5)	10.6 (3.8)	10.1 (4.0)	9.4 (2.5)
Normal Halo-Vest Application	0.4 (0.2)	4.2 (2.9)	0.2 (0.1)	0.3 (0.2)	0.2 (0.3)	0.3 (0.3)	0.6 (0.6)	0.6 (0.3)
Vest Loose	0.4 (0.5)	6.8 (3.8)	0.2 (0.2)	0.9 (1.3)	0.4 (0.4)	0.8 (0.8)	0.9 (0.7)	0.3 (0.3)
Removal of Posterior Uprights	2.2 (2.7)	19.7 (5.4)	1.3 (1.1)	1.7 (1.6)	1.3 (1.1)	1.6 (1.8)	0.7 (0.5)	2.1 (1.5)
Superstructure Loose	2.7 (2.1)	22.3 (13.2)	1.1 (0.7)	1.8 (1.7)	1.2 (1.0)	2.1 (1.6)	2.5 (2.5)	1.7 (1.4)
C) Lateral Bending								
Physiological	9.1 (1.8)	14.2 (8.9)	9.5 (3.8)	7.2 (0.5)	4.7 (1.3)	5.6 (2.0)	4.1 (1.8)	5.6 (1.8)
Normal Halo-Vest Application	5.4 (2.0)	2.3 (2.1)	0.8 (1.1)	0.8 (0.7)	1.0 (0.8)	2.8 (1.7)	4.5 (1.2)	3.7 (1.5)
Vest Loose	7.9 (2.5)	3.7 (2.4)	1.7 (2.7)	2.2 (2.1)	2.1 (1.5)	4.5 (1.5)	7.6 (4.1)	5.1 (1.5)
Removal of Posterior Uprights	10.4 (2.8)	3.8 (2.1)	1.9 (1.8)	2.9 (2.2)	3.9 (1.9)	5.9 (1.6)	8.4 (4.1)	6.3 (2.4)
Superstructure Loose	11.5 (1.5)	8.1 (4.5)	3.0 (1.6)	1.8 (1.6)	6.0 (2.9)	7.1 (2.7)	$10.7^{\#}$ (4.0)	8.2 (3.2)

FIGURE CAPTIONS

Figure 1. Photograph of the skull-neck-thorax model with the halo-vest used to study the effect of halo-vest components on spine stability. The global coordinate system (XYZ) was fixed to the ground with its positive X-axis directed to the left, positive Y-axis oriented superiorly, and positive Z-axis oriented anteriorly relative to the specimen in neutral posture. See the text for further details of methodology.

Figure 2. Flexibility testing protocol in which peak pure moments of 10 Nm in flexion-extension, axial torque, and lateral bending were applied in four equal steps, while the motion data were recorded on the third loading cycle. The rotation-moment curves and the total range of motion (RoM) were determined for each spinal level.

Figure 3. The three-dimensional coordinate system (xyz) fixed to a moving vertebra. The coordinate system was established to determine the motion of each vertebra relative to the directly inferior vertebra. The origins were fixed to the posteroinferior corner of each vertebral body, C2 through T1, and to the posterior border of the posterior arch of C1. The positive x-axis was directed to the left and was perpendicular to the mid-sagittal plane; the positive y-axis was oriented superiorly, and the positive z-axis was oriented anteriorly through the anteroinferior corner of each vertebral body for C2 through T1, and through the anterior border of the anterior arch for C1. The broad arrows illustrate pure moments, while the thin circular arrows demonstrate the rotations in flexion, extension, axial rotation, and lateral bending.

Figure 4. The average rotation-moment curves for each spinal level, C0/1 through C7/T1, and head/T1 for normal halo-vest application, loose vest, loose superstructure, and removal of the posterior uprights: A) flexion/extension, B) axial torque/rotation, and C) lateral bending. Please refer to **Figure 3** for the rotation and moment directions. To improve readability, the plot symbols and error bars are slightly offset. Note that the rotation scales are different for head/T1 (±30°) and the spinal levels in flexion/extension and axial rotation (±20°) and lateral bending (±10°).

Figure 5. The average total ranges of motion (RoM) in flexion/extension of the present study with normal halo-vest application. Also shown are the average *in vivo* data from radiographic studies of symptomatic patients wearing a halo-vest while performing voluntary active neck flexion/extension or activities of daily living, including transitioning between supine, seated, and upright postures.[3,4,16-18]